Safety Guide 100

DESIGN GUIDE FOR PACKAGING AND OFFSITE TRANSPORTATION OF NUCLEAR COMPONENTS, SPECIAL ASSEMBLIES, AND RADIOACTIVE MATERIALS ASSOCIATED WITH THE NUCLEAR EXPLOSIVES AND WEAPONS SAFETY PROGRAM

CHAPTER 3.0

THERMAL ASPECTS

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FIGURES

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ACRONYMS

CFR	Code of Federal Regulations
DOE	Department of Energy
DOT	Department of Transportation
IAEA	International Atomic Energy Agency
QA	Quality Assurance
SARP	Safety Analysis Report for Packaging

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3.0 THERMAL ASPECTS

3.1 INTRODUCTION

3.1.1 Scope

This guide is applicable to packages that are to be used to transport radioactive weapons components, radioactive special assemblies, and special nuclear materials. The purpose of this guide is to help the designer of these packages deal with the thermal issues that must be addressed to ensure the safety of the public and the integrity of the package. It is assumed that the user of this guide is generally familiar with the field of heat transfer, although no advanced knowledge is required. This guide also generally assumes that Type B packaging is being designed unless otherwise stated.

The intent of this guide is to bring together useful information that can be used during the design phase of package development. Instead of trying to place all of the information necessary for package design in this single guide, the purpose is to give a basic understanding of the principles involved. Additionally, in some cases, references are given that direct the designer to more detailed information. This guide includes brief descriptions of regulations which must be satisfied to have packages certified for use (Subsects. 3.2.1 and 3.2.2) and, probably more importantly, references that tell the designer exactly where both the regulations and interpretations of regulations can be found. Information is also given concerning basic package design, calculational methods for design work, and (briefly) methods of proving compliance in a Safety Analysis Report for Packaging (SARP).

The discussion of the basic design of the package is broken into several groups: first, a section about design questions dealing with either components or physical features of the package itself (Sect. 3.2.3), and second, a section that addresses the importance of any heat source that can be associated with the package content (Sect. 3.2.4). Specifically, this section discusses different design strategies depending on whether the package contents generate a relatively large amount of heat or a small amount of heat. The final section of this chapter deals with designs that have been used before in the weapons complex, including both failed and successful designs. It is hoped that by including designs that have failed, similar mistakes can be avoided and resources conserved.

A discussion of the calculational methods that may be used during design, including a variety of techniques from simple to advanced, can be found in Sect. 3.3. For the simple methods, a special emphasis has been placed on giving examples, whereas for the more advanced methods, the emphasis is on a general description coupled with references for more detailed explanations.

The fourth section deals briefly with methods of meeting the requirements that are specified in the Code of Federal Regulations (Sect. 3.4). A successful design will ultimately result in a packaging certificate being issued based on a SARP, which shows conformance to the guidelines set forth in the federal regulations. Although this guide is not intended to deal with these issues in detail, a discussion of package design would not be complete without some information regarding these regulations and how to meet them.

The final section, Sect. 3.5, describes Quality Assurance activities which should be part of a package's thermal design.

3.1.2 Approach

This guide is not intended to contain a recipe for designing all packages. The design of a new package needed in the weapons complex represents a challenge. The fact that a new package is required indicates that the packaging need is unique (otherwise an existing package could be used). Along with this challenge may come some details that can not be foreseen. Thus, it cannot be guaranteed that all future questions are answered in this document. Although this guide does contain some emphasis on past mistakes made by package designers, it is impossible to anticipate all future problems. Following this guide does not assure certification of a package design.

Much of the text reflects lessons learned during the certification process. Individuals in the weapons complex were consulted and information gained from them is included in this guide.

This guide is intended to assist the designer of Type B packages. The guide cannot address all possible circumstances and, therefore, it is the responsibility of the designer to apply good engineering judgement. Following this guide in no way alleviates the designer's responsibility for the package and its impact on public health and safety and the environment.

3.2 THERMAL DESIGN CONSIDERATIONS

3.2.1 Applicable Regulations

To have a package certified for the transportation of radioactive materials (i.e., weapons components, special nuclear assemblies and special nuclear materials) all of the qualifications stated in the Code of Federal Regulations (CFR) No. 10, Part 71 (10 CFR 71), titled *Packaging and Transportation of Radioactive Materials*,[1] and 49 CFR Parts 100-178 must be met.[2] Although the CFR forms the basis for certifying a radioactive material shipping package for use, other regulations, U.S. Department of Energy (DOE) Orders and Department of Transportation (DOT) regulations, that must be met for the shipment of weapon components and special nuclear assemblies. These requirements are fully outlined in Chap. 1 of this document. For thermal aspects, the tests for qualification are specified in 10 CFR 71, Subpart F, which contains the sections 10 CFR 71.71, *"Normal Conditions of Transport,"* and 10 CFR 71.73, *"Hypothetical Accident Conditions."* Currently, proposed revisions to 10 CFR 71 are being considered. These revisions would bring packaging requirements in the United States more in line with those of the International Atomic Energy Agency (IAEA) which used elsewhere in the world. In most cases, the proposed changes are slightly more stringent than the current regulations. These changes are expected to be approved in the near future. Specific regulations referred to in this chapter are from the proposed revisions.

3.2.2 Requirements Relating to Thermal Issues

This guide does not describe procedures for testing (analytically or physically) for the certification of a proposed package design. According to the regulations, the testing requirements are the design criteria for the package; thus, it is impossible to separate package design from certification requirements. The following section describes the various requirements outlined in 10 CFR 71 and how they affect the design process.

3.2.2.1 Specific thermal requirements

In general, two modes of package transport are addressed in the regulations—normal and accidental. Normal refers to conditions the package may experience on a typical operating day, and accident refers to a series of abnormal events in which the package may be damaged. The circumstances that constitute each of these conditions are stipulated in 10 CFR 71.

For the usual case (Type B packaging), the most severe thermal environment that the package must be able to withstand is a hypothetical accident involving an 800°C (1475 °F) fire that lasts for 1800 s (30 min). The package is exposed to this environment after a series of other accident conditions, including a 9-m drop onto an unyielding surface and prior to immersion in 15 m of water. After this series of tests, the integrity of the package must remain such that the public is not placed at risk during or after such an accident. It is not required that the package content remain operable through this test, only that containment and shielding be intact and that a criticality event does not occur in the ease of fissile material. Additionally, certain normal conditions of transport scenarios exist that are not nearly as rigorous. However, both the package and its content must not only survive these conditions but also be fully functional after these conditions have been met. Following normal conditions of transport a package may appear visually fully functional, however it must be shown that there is no substantial reduction in the effectiveness of the package (refer to 10 CFR 71.43(f)).

Normal Conditions

For normal conditions of transport, some thermal regulations explicitly apply to the package. The normal conditions are divided into two different categories, shaded and insolated. It may be necessary to perform calculations based on each of these situations. Additionally, normal condition regulations differ depending upon method of shipment (exclusive use or non-exclusive use shipments).

For the shaded case, 10 CFR 71.43 (g) requires that, for the package to be shipped in a nonexciusive shipment, it must have no accessible surface with a temperature greater than 50°C (122^{0}F) when placed in shaded, still air at 38°C (l00°F). For an exclusive-use shipment, the temperature limit is 85°C (185°F) for the same ambient conditions.

No specific quantified thermal requirements exist for the insolated case; however, the package must remain fully functional (i.e., with respect to containment, shielding, and criticality) when exposed to the stipulated heat flux and all materials of construction must remain stable and useable. Included in 10 CFR 71.71(c) is a table containing solar heat flux, data to be used for calculational.

One additional requirement in 10 CFR 71.71 (c)(2) is that a package must also remain fully functional when exposed to an ambient temperature of -40°C (-40°F). The most common problem for packages at lower temperatures is associated with metal components becoming brittle and thus susceptible to cracking. Most metals undergo a distinct physical change at some low temperature, which causes the material to become much more brittle. The property is often referred to as the ductile/brittle transition temperature. All major metal components (and possibly all metal components) chosen should have a ductile/brittle transition temperature of less than -40°C. Additionally, some components that are not made of metal may become brittle or just generally lose the ability to perform some of the functions for which they were selected. Seals are likely source of problems at low temperatures. Some elastomeric seals may lose the elastic properties that allow them to seal, while metal seals may shrink so much that containment is lost.

Accident Conditions

The thermal accident condition specified in the federal regulations is generally an 1800-s, 800°C hydrocarbon fuel fire. Specifics concerning the hypothetical thermal accident test are found in 10 CFR 71.73(c)(3). Although it is not necessary for the package to remain fully operable throughout the duration of the test, criticality and shielding functionality must remain intact. Additionally, containment of the radioactive material must continue, although the definition of containment is somewhat altered (lessened) when compared with that for normal conditions.

3.2.2.2 Other requirements affected by thermal aspects

Most failures of packages due to thermal insult are caused by some component being overheated, which results in some change in physical properties of the component (i.e., melting of a seal that allows release of material being shipped). Other forms of failure due to thermal insult can be the result of thermal expansion or constriction. Most materials experience a change in density when heated, and the vast majority of materials expand during this process. Generally, two phenomena of this type should be accounted for in the design of a shipping package: expansion of gases as well as expansion and phase change, including both liquids and solids.

3.2.3 Package Features and Their Thermal Requirements

This section discusses how the various features of a package relate to thermal conditions surrounding the package. The package features are divided into two categories: package performance components (Subsect. 3.2.3.1) and physical systems (Subsect. 3.2.3.2). In general, the package performance components comprise the actual functions the package will perform, whereas the physical systems are the actual systems that perform these functions. Material properties that affect thermal performance are discussed in the physical systems category.

3.2.3.1 Package performance components

A package must be designed to ensure the safety of the public by maintaining containment of the material being shipped, by shielding from any radiation produced by the package content, and by providing a geometry that prevents a criticality event. The impact of thermal issues is discussed in the following paragraphs with reference to each of their functions.

Containment

The most likely breach of package integrity due to thermal incident circumstances is a loss of containment. Containment criteria defined in 10 CFR 71 (detailed discussion of these criteria is found in Chap. 4) are different for some various isotopes. The loss of containment is most likely to occur when a seal on the inner container fails and allows some or all of the package content to escape. The failure of this seal as it relates to thermal insult is most likely during or after an accident scenario such as a fire. Therefore, it is important to know the maximum temperature the seal can withstand. A leak rate of A_2 per week is permissible after such an accident scenario.

Shielding

To protect the public and the environment, packages used to transport either neutron- or radiation-emitting materials must employ some type of shielding. Typically, radiation shielding is performed by a dense material with a high Z number (i.e., lead), and neutron shielding is performed by a material with a high atom concentration of low mass number (i.e., hydrocarbons). For packages with relatively low emission rates, it may be possible for the metallic components of the containment system to provide the shielding properties. The most common loss of shielding incident due to a thermal incident would occur as a result of some type of phase change in the shielding material. Generally, this is not a problem for weapons packages, but loss of shielding due to either the melting of shielding material (i.e. radiation shield) or burning or pyrolysis (i.e. neutron shield) can result in severe circumstances. Examples of loss of shielding include combustion of hydrogenous materials or decomposition of plastic materials that are used as shields. A general design guideline would be not to take credit, for shielding purposes, for any material that may be lost during a thermal (or any other type) accident. When making assumptions in the package design phase, it is best to be very conservative concerning what and how much material may be lost during an accident. Limits should not be pushed when shielding systems are designed.

Criticality

Generally, criticality control is provided by geometric spacing and containment sealing. In some cases, it is possible to create a criticality event by simply flooding the contents of a package. Thus, containment is a crucial factor in ensuring that criticality events do not occur. Chapter 6 discusses the specifics about criticality and Chap. 4 addresses seal design and containment control. Safe geometric spacing is provided by designing packages such that even if several packages contact one another, it is impossible for their contents to be close enough to cause a criticality event. In criticality control, it is necessary to consider a situation resulting in the worst possible damage to the package. Criticality problems caused by thermal events would normally be associated with either of two events: loss of insulating material used to control geometric spacing; or physical change in a material used as a poison (i.e., melting) which would make it ineffective. Worst-case scenarios must be considered when designing criticality control systems.

3.2.3.2 Physical systems

This section includes a discussion of the various systems contained on some or all packages that are used to ensure that various thermal situations that may be encountered by the package do not adversely affect the performance of the package.

Thermal Protection

This section includes a discussion of the various methods by which heat is either kept out of (under accident conditions) or removed from (due to significant internal heat generation) a package. For completeness, a section discussing various physical properties that relate to thermal issues has been included.

Features (insulation, fins, conduction paths, etc.). Packages used in the shipment of radioactive material must be capable of withstanding intense thermal environments while preventing the release of contents and maintaining shielding and nuclear subcriticality. Achieving this capability requires use of construction materials that enable the package to withstand serious thermal insult. Insulating materials are usually used to slow the transfer of heat toward the package content during a thermal accident condition. Often, the material used to provide this thermal protection is also used to increase structural stability. For packages designed to carry contents with significantly large heat sources, the issue of thermal protection becomes much more complicated. For this case, the insulating material must work effectively to reduce the heat added to the package during an upset condition while allowing internally generated heat to escape under normal conditions. These are conflicting requirements that must be carefully balanced during the package design process.

Other forms of thermal protection can be employed as long the systems are passive in nature. Passive systems, such as heat pipes, can be used, but their viability in the event of an accident must be demonstrated before package certification. Fins can also be used to increase the rate of heat transfer from the package content to the package's surroundings. However, fin cooling systems can also increase the rate of heating to the interior portions of the package during an accident scenario. One possibility is to make the fins of a material that is stable at lower (normal condition) temperatures but experiences a phase change at elevated temperatures (accident condition). The problem with this design theory is that, while the fins may melt when exposed to the accident scenario outlined in 10 CFR 71 (i.e. 800°C), they may not melt if they were near but not fully immersed in such an accident. In this case, it is possible for the fins to stay intact and actually increase the quantity of heat absorbed by the package.

Conduction pathways can be used to help remove heat from the inner container on packages with a significant internal heat generation. Any type of high thermal conductivity material can be used as long as it does not interfere with any of the package's other functions. Special care must be taken to ensure that such pathways do not allow heat an easy access to sensitive portions of the packaging during a thermal accident situation.

Thermophysical Properties. Several properties affect how a material or group of materials will respond to a thermal input. The discussion of these properties here is brief, and more information can be found in most standard heat transfer texts. Several typical undergraduate level heat transfer texts are referenced (this list is not exhaustive).[3][4][5] and [6]

Thermal conductivity is a measure of a material's ability to conduct heat. Units for this quantity are expressed in W/m-K, or more explicitly W-m/m^2-K. Metals tend to be the most conductive class of materials, but conductivity within this group varies greatly. Of the common materials used for construction of packaging parts, aluminum is the most highly conductive with a thermal conductivity of about 240W/m-K. Carbon steel has a much lower conductivity of about 60 W/m-K, and stainless steels have an even lower conductivity of about 15 W/m-K. Insulating materials, as their name suggests, have a much lower thermal conductivity, typically on the order of 0.05 W/m-K, but this number is somewhat misleading. Most insulating materials employ air pockets or gaps. Through this region of the material, heat transfer is actually by natural convection and radiation, not conduction. In most cases, these other heat transfer mechanisms are less efficient than conduction; thus, the overall thermal conductivity of the material is very low. In general, solids are more conductive than liquids, which are more conductive than gases. However, insulating materials (which are usually considered solids) often display thermal conductivities equal to or less than that of some liquids and gases since these materials are actually a mixture of solids and gases. Thermal conductivities of common materials can be found in most heat transfer texts. For less common materials, Touloukian has published a very extensive compilation of thermal conductivities.[7] Only the thermal conductivity of a material is needed to calculate steady state conduction heat transfer rates.

Specific heat is a measure of the amount of energy it takes to heat a specified quantity of a material a specified number of degrees. The units for this property can be expressed in kJ/(kg-K). The heat capacity of most materials increases with temperature. Density is the mass per volume of a material and units are kg/m^3. For most materials, density decreases as temperature rises, although some materials may contract. All three of the material properties that are discussed so far (thermal conductivity, heat capacity, and density) are needed to calculate non-steady state conduction heat transfer rates.

The only material property needed to calculate heat transfer rates due to radiation is emissivity (or absorbtivity). Emissivity is a measure of how efficiently a surface of a material emits radiant energy compared with an ideal radiator (blackbody). The emissivity of a material surface can vary greatly depending on the finish of the surface. For instance, the emissivity of stainless steel can vary from 0.17 (highly polished) to 0.90 (oxidized) depending on the finish of the surface.[3] However, the advantages of selecting a material of construction with a low emissivity, although it may actually help to protect a package, are diminished by current interpretations of guidelines set forth in 10 CFR 71. Because attaining, keeping, certifying, and documenting a specified surface finish on a package part may be difficult, this interpretation may well be valid. Most applications of radiative heat transfer dealing with a package are for the package surroundings to the package exterior (or vice versa). However, if gaps exist within the package, heat transfer across these gaps will be by radiation and convection (unless the space is a vacuum, in which case heat transfer is only by radiation).

Several properties must be known for the calculation of convection heat transfer, and they will always be fluid properties (i.e., either gas or liquid). The fluid properties needed to calculate the natural convection heat transfer coefficient are dependent on the correlations used, but generally the properties are fluid viscosity, density, volumetric thermal expansion coefficient, thermal conductivity, and heat capacity. For the vast majority of cases, the fluid will be air, although some other liquids, such as nitrogen and helium, are used in package design. Properties for these fluids can be found in most heat transfer texts.

One of the most important physical attributes involving thermal aspects of package design is decomposition of construction materials at elevated temperatures. This type of process is usually associated with compounds such as natural fibrous materials and compounds used to make seals (i.e., rubbers, etc.). Many forms of decomposition exist, from simple dehydration to pyrolysis to actual combustion. Dehydration is the act of vaporizing free water (H_2O molecules that are not bonded to other molecules), which typically then leaves the material (the vapor is driven off by a buoyancy gradient). Dehydration is usually the first step in decomposition for most materials which contain free water. Because a significant amount of energy is required to vaporize the water to steam, this acts as an important method of heat absorption. In fact, one of the reasons that the common insulating material Celotex™ is such a good material for protection during a thermal accident is that it naturally contains a large volume of free water, which goes through the process described above at temperatures near 100 °C. During this process, energy that would have otherwise gone toward heating the package is used to make steam, which, for the most part, then escapes the package. Although the loss of free water to vaporization is usually good for package thermal characteristics, the loss of the hydrogen molecules may negatively affect the package's shielding capabilities. Obviously, there needs to be some sort of trade-off, such that shielding remains intact while interior package temperatures do not increase enough to cause a loss of containment. Design calculations should be conservative in nature.

Further decomposition can take place as temperatures rise. If the decomposition process proceeds with oxygen present, the result typically is combustion; if oxygen is not present, the process is pyrolysis. These processes can be either exothermic or endothermic and should be examined for each material that is considered for construction of a thermal barrier or structural impact limiter. If these processes are endothermic, like the dehydration process, these processes may in fact assist in keeping the package interior from experiencing crippling thermal exposure. Typically, the decomposition process-whether it be combustion, pyrolysis, or a combination—is very complicated, especially for natural materials that are not homogeneous. For most cases, the specifics of the decomposition process are not fully characterized; thus, conservatism is important when dealing with this aspect of package design.

Structural Design Features that Affect Thermal Aspects

A measure of the rate at which different solid materials expand or contract is called the coefficient of thermal expansion. Typically, the rate of expansion of a material is expressed in one of two ways, as linear expansion or as volumetric expansion. Units for these properties are expressed either as cm/cm-°C or as cm^3/cm^3-°C, respectively.

Under normal circumstances, only metallic members contain enough structural strength to damage other parts; thus, linear thermal expansion is usually considered only in relation to metal parts. The anticipated expansion of a member is calculated as a product of the estimated change in temperature due to thermal assault, the thickness of the member, and the coefficient of thermal expansion. The resulting answer will have units of length and will indicate the change in the dimension of the member being considered.

Volumetric thermal expansion is most often associated with seals. If a seal shrinks considerably under cold conditions, the water-tight or leak-tight seal may be lost; thus, containment may no longer be intact.

Consequences of linear thermal expansion problems as they relate to container structural integrity are covered in Chap. 2; consequences of volumetric thermal expansion (or shrinkage for lowered temperatures) are discussed in Chap. 4. In general, linear thermal expansion problems can easily be avoided by any one of several methods. These methods include designs that leave enough clearance between adjacent package parts to allow for thermal expansion, the selection of materials that have an increased coefficient of thermal expansion from the center to the outside of the package, or the use of similar materials of construction such that the coefficient of thermal expansion is the same for all metallic materials. In general, volumetric thermal expansion problems can be avoided by careful selection of sealing materials such that seals will remain intact at low temperatures.

Expansion of fluids contained within a package can create high stresses on structural members of the package. Generally, gases expand at a rate that is nearly linear with absolute temperature. Liquids expand, too, but not as greatly. The largest change in volume for a fluid involves a liquid that is heated to the boiling point and initiates a change of phase to gas. In this case, change of volume, or consequent change of pressure, can be very severe, thus stressing structural members. This subject is covered more thoroughly in Chap. 2.

Pressure Vents, Valves, etc.

In general, the use of pressure vents and valves is discouraged on packages in the Weapons Complex. Pressure vents and valves should be used only if they are absolutely necessary and must comply with 10 CFR 71.43(e). If they are used, the concept of a fail-safe mode must be applied, and regulators must be convinced that a fail-safe situation does exist.

3.2.4 Payload-Dependent Strategy

By definition, packages that carry radioactive materials have internal heat generation. The source of this heat is energy given off by the natural radioactive decay of the package content. In most weapons complex applications, the amount of heat given off by the contents is negligible i.e. the amount of decay heat is so small that it does not appreciably affect package performance. As previously mentioned in Subsect. 3.2.3.2, thermal design of packages is much more complicated for a package that contains a significant heat source (for the weapons complex, this situation is generally limited to certain plutonium isotopes and their oxides). If a package does not contain a significant heat source, the sole function of the thermal portion of the design is to keep heat away from the containment vessel. When a significant internal heat source exists, thermal protection from ambient conditions can cause high containment vessel temperatures.

3.2.4.1 Payload with weak heat source

In general, when a package is being designed for shipping a material that is not a strong heat source, the emphasis of the thermal design is on being able to withstand a postulated accident condition.

For this case, the highest surface temperature under normal conditions of transport for an uninsolated container is equal to the ambient temperature (i.e., 37.8 $^\circ$C).

Conditions caused by direct insolation could possibly cause degradation of some materials of construction. If the maximum temperature reached on the exterior surface of the package, when isolated, is less than the minimum degradation temperature for all of the materials of construction, only accident conditions need to be considered in the thermal portion of the design process although this fact must be explicitly stated in the SARP. For most cases, the maximum exterior package temperature with direct insolation is less than 100°C, and constructing a package of a material that would degrade at such a low temperature would be somewhat unusual.

If no materials with low degradation temperatures are called for in the design of the package, the main area of concern for a low heat source package is with respect to the hypothetical thermal accident. Obviously, the main strategy is to not allow enough heat into the package to damage the seal which ensures containment. The most common method for doing this is to use a thick layer of thermal insulation between the inner containment vessel and outer drum. Most current designs use a single material as both an insulator and a primary impact absorber.

Some crushing will usually occur when a package is subjected to the 9-m drop. This crushing of the insulation can cause changes in the thermal properties of the insulating material. Usually, crushing of an insulating material containing air pockets tends to push the air out and smash these pockets. These changes result in not only an increase in the material's density but also an increase in the material's thermal conductivity. For this reason, it is important to understand the method through which the chosen insulation material works such that changes caused by dropping or crushing can be accounted for when determining or estimating material effectiveness.

For most materials currently used for thermal insulation, decomposition during a thermal accident must be a design consideration. Typically, the decomposition of the material creates a large volume of offgas. Very serious pressure buildups can occur if some type of pressure venting system is not included in the package design. Most pressure release systems are simply holes drilled in the outer confinement drum. These holes are typically small in diameter (less than 1 cm). Package designs with from one to twelve pressure relief holes have been shown to be successful. Some holes are simply left open, whereas others are sealed under normal conditions with some type of melt-out plug or Teflon™ tape, which will disappear in thermal accident situations. The consequences of not including such devices could be severe, up to and including the possibility of outer confinement drum rupture, subsequent complete combustion of insulating and shielding materials, and loss of containment. This decomposition process can also cause the loss of hydrogen atoms contained within the thermal insulation/impact-limiting materials. The hydrogen present in this material often is part of the package’s shielding system; therefore, possible loss of material during thermal insult must be considered when designing shielding protection.

3.2.4.2 Payload with strong heat source

When materials such as plutonium or its oxides are transported, radiated energy from the material will cause the interior portions of the package to heat, greatly complicating the matter of designing a package to transport this material. Without the heat source, the only objective of the thermal design of a package is to keep heat from getting into the package. For the case with a heat source, heat generated by the package content must be able to leave the package while it is still necessary to keep accident heat out of the package. In general, when there is no heat source, the more effective the insulation material, the better the job it will do. When there is a heat source within the package, a very effective thermal insulation may cause the interior portions of the package to overheat even under normal conditions.

There is no simple, fool-proof method for designing a package with a sizable heat source. The easiest way to deal with such a problem is to use a large quantity of a thermal insulation that is not the most efficient available. However, this method is not necessarily the most economical route. Package size or transport index (see Chap. 1) usually determines the number of packages that can be sent on a single shipment. The larger the package, the fewer the number of packages that can be shipped in a single load. For some packages, such as exclusive-use packages, this limitation might not be a major factor, but it is a factor for smaller packages.

Other design strategies can be employed. One such design is to use heat transfer fins connected to the inner container and protruding outward into the thermal insulation area. This design will facilitate the transfer of heat out into the insulation and, in general, will keep the temperature near the inner container seal lower than if the fins were not there. Obviously, the fins cannot protrude all the way out to the outer confinement drum, because this would simply wick heat into the inner container during insolated and accident scenarios. The farther out the fins protrude, the more effective they will not only be at reducing inner container temperatures under normal uninsolated conditions but also at transferring heat into the package under up-set conditions. If such a design is to be used, it will be necessary to fully analyze the package for both insolated and accident conditions.

Another possible design ploy is very similar to the preceding design. It is possible to use a material just outside the inner container (or possibly just outside the heat source but within the inner container)that has a relatively high thermal conductivity(when compared with typical thermal insulation). Outside this material would be a layer of thermal insulation. The effect of the high thermal conductivity material would be to spread out the heat generated by the package such that maximum temperatures near the inner container seal would be less. This method can also be used inside the inner container to keep the temperature of the content below a certain level, as is sometimes required to keep the content in a usable state. The layer of insulation would then provide thermal protection from insolation and accident heat sources. One recognizable problem with this design strategy is that the thermal insulation layer may be damaged or breached by drop or crush tests, thus allowing heat almost directly into the package. This possibility may be avoided by placing another layer of a structural material outside the thermal insulation. It is the rare case where there is enough room to accommodate such a three-layer cross section, especially when minimal package size is desired.

Another thermal package design strategy is to make a package very massive. If the package is large and heavy enough, it will heat very slowly during a thermal accident. This design method may be acceptable for some exclusive use shipments, but in general, the cost of using such a large package will not be justifiable. Similar to this design strategy is the idea of making a package, including all seals, all metal. If the content can withstand a high temperature, this option may be feasible. However, metal seals tend to have difficulties remaining sealed at the low temperatures required for packaging certification.

3.2.5 Container Design Example Section

Many successful package designs have been certified as meeting government requirements and are now in use. These designs represent the culmination of a rigorous development process. It is probably safe to say that the majority of these design efforts, at some point during the design process, had some inadequacies. This section discusses both successes and failures that have occurred in package design within the weapons complex. Problems from previous designs are discussed in the hopes that these pitfalls can be avoided in future designs; successful designs are presented so it will be unnecessary to "reinvent the wheel" every time a new package is needed.

3.2.5.1 Failed designs

As with any product that is continually being improved, some design proposals simply do not perform very well. Most of these ill-fated proposals are weeded out early in the design process, but a few may actually be included in package designs that are built. Also, a design that initially works very well possibly will not perform as well at a later time. This section attempts to describe some of the problems that have been encountered with earlier weapons complex transportation packages. No doubt the list is not comprehensive, and the list may need to be updated as new failures are experienced in the future.

One package design, based on a thin-shelled drum with Celotex™ as the primary insulation and impact limiter, was designed such that some portions of Celotex™ were less than 7.5 cm (3 in.) thick. This design was required because the inner container that had been designed was quite large in relation to the outer confinement drum that had been selected. The inner container design was fairly typical in that it was a cylinder with a bolted-flange lid at the top. Unfortunately, this flange design dictated that the outer edge of the flange would be within 7.5 cm of the outer confinement drum. The flange area, obviously, contained the seal that ensured containment of the package contents. During thermal testing, Celotex™ degradation in this area was quite severe, and test results indicated that the seal had failed. Hence, the package could not be certified for use as devised, and some reworking of the design was necessary. Celotex™ in the area adjacent to the flange was replaced with a ceramic fiberboard that was judged to be more resistant to thermal insult. Presumably, the ceramic fiberboard did not possess the structural qualities of the Celotex™ (i.e., impact limiting); thus, not all of the Celotex™ was replaced. Two issues were partially responsible for the failure of the package: heat that was conducted through the Celotex™ to the seal and hot offgasses from the Celotex™ were reaching the area around the inner seal. Thus, it was necessary to specify a tighter packing arrangement such that gaps between layers of the ceramic fiberboard near the flange would be reduced and pathways for offgasses to the flange would be minimized. The rework of the design has been successful, and subsequent thermal tests have been passed.

Some packages had problems with outer confinement drum closure designs. At first glance, this type of design problem would be considered a structural flaw rather than a thermal problem, and in reality the problems have been remedied with structural fixes. These problems are discussed in this section because the package's thermal performance was decreased due to these structural inadequacies. In one case, a package that had been certified for use was being re-evaluated for recertification. The design was a simple drum-type package that used a cellulitic fiberboard for thermal insulation and impact damage resistance. The outer confinement drum was closed by a simple retaining ring that used a single bolt for tightening. During the re-evaluation process, the lid came completely off one of the test units. This result was surprising, as extensive initial testing of the package, when it was first certified, showed no indication that lid loss was a possibility. This unexpected result did not result in a thermal failure only because the thermal test was not performed. Had the test been performed, a "worst orientation" of the package for the test would have been one in which the package was inverted, and presumably the inner container and the insulation would have fallen out of the package. Undoubtedly, this "orientation" would have led to a thermal failure.

A similar incident occurred to a new package that was undergoing initial certification testing. This package was not a typical drum-type design but rather was a large, thick-walled horizontal cylinder. The design was basically two cylindrical half shells that came together at a flange on the horizontal plane. The flange was bolted around the perimeter of the package. The package also had 12 pressure relief holes (~ 1 cm diam.) arranged symmetrically around the package (four rows of three holes every 90° around the package). When the package was drop tested, some opening at the corner of the flange occurred on some of the prototypes. The openings were as wide as 3 to 5 cm and up to 10 cm long (around the corner). Although flange splitting to this extent had not been expected by package designers, some splitting had been expected. To combat this occurrence, the package interior near the flange had been lined with an intumescent material that was supposed to expand when it was heated and fill any gaps in the flange.

After the packages were thermally tested, the intumescent strip obviously had not been successful; visual inspection showed no evidence of the intumescent material. Other packages using the same cellulitic material for thermal insulation had been known to continue to burn and smoke for about 15 to 30 min after the end of the thermal test. The packages with the opened flange, on the other hand, continued to smolder for nearly three weeks. Although the rate of burning of the material over this time was obviously very slow, it was still an indication that temperatures within the package were quite high. After the packages stopped smoldering, the packages were opened and the containment seals were still intact. Nonetheless, it did not seem certain that all packages of this design that smoldered for such a long period of time would remain sealed, and the flange design was changed. Subsequent tests showed that the flange no longer opens on impact.

It has been suggested that the continuous burning of the fiberboard was actually the result of the large number of pressure relief holes on the package rather than the opening of the flange. The argument was that the placement of the holes along and around the package created somewhat of a chimney effect. However, for all the packages thermally tested in which the flanges did not open significantly, all burning of package materials ceased within an hour of the end of the thermal test. This is not to say that the proliferation of pressure relief holes did not contribute to the problem of the packages that did burn. Rather, it suggests that contribution to the burning of package materials by the vent holes was not significant enough to cause package failure.

The lesson learned here is that if a design allows too much of a cellulitic material to be exposed directly to the thermal conditions present during and after a hypothetical thermal accident test, the material will more or less continue to combust until all of the material has degraded. Thus, precautions should be taken during the design phase to ensure that exposure of such material is limited.

The use of holes in the outer confinement drum for pressure relief during thermal testing is a design feature common to virtually all weapons complex transportation packages. To keep water from entering the package during normal use conditions, these holes are often plugged with some sort of seal. A common seal is made of plastic and melts when the package is exposed to conditions that would be likely to cause package pressurization. One design called for the holes to be covered with a stainless steel tape; however, it was not clear if the tape was on the inside or the outside of the outer confinement drum. Apparently the designer thought that the tape would look good because the rest of the container was also stainless steel. The designer had assumed that the tape would lose its tackiness during thermal testing, allowing the vent holes to function as they were designed. When the first package was tested, however, the tape sealed very tightly rather than peeling back. When the thermal test was complete, the package was visibly bloated, and some people worried that it could explode. Eventually, the package cooled and returned to its normal shape without incident, but the stainless steel tape was not used again to cover pressure relief holes.

These are just a few of the problems designers have encountered with thermal aspects of packages. Some of the reasons for failure are fairly obvious whereas others are not. Although it is unlikely that a future designer will encounter these same situations, reading these examples may help the designer think about possible malfunctions and fixes in a design he may be considering.

3.2.5.2 Successful designs

Many package designs, have been successful. Ranging from very simple to quite complex, packages with very small heat sources tend to have the more simplistic designs, whereas those with sizable heat sources tend to be more extravagant. This section will describe some of the various designs that have proved successful over time.

The simplest and most common package design now used in the weapons complex is a stainless steel inner container surrounded by a thick layer of material (usually cellulitic fiberboard) that acts as both a thermal insulation and an impact limiter (Fig. 3.1). This layer is then surrounded by the outer confinement drum, which is generally constructed of either mild or stainless steel. This very basic design is usually used only for packages with contents that have a negligible heat output. If some very basic design strategies are followed, this package design can be effective and relatively inexpensive. The main concerns with this type of design are the use of the cellulitic fiberboard and its propensity to offgas when exposed to high temperatures. This property makes analytical modeling of the hypothetical thermal accident almost impossible unless an extremely conservative approach is taken. Offgassing notwithstanding, this design has repeatedly been able to withstand the rigors of the hypothetical thermal accident environment without loss of function.

A more sophisticated version of this design uses two layers of thermal insulation/impact- limiting material. These two layers are sealed off from one another by creating compartments for the two layers (Fig. 3.2). The outer most compartment contains the insulating material, which will be exposed to the most severe thermal conditions. Due to compartmentalization. offgas from the outer most layer cannot reach the outside of the inner container, but rather can reach only the outside of the metal wall that forms the compartment. The insulation/impact limiting material used for the inner layer is different from that

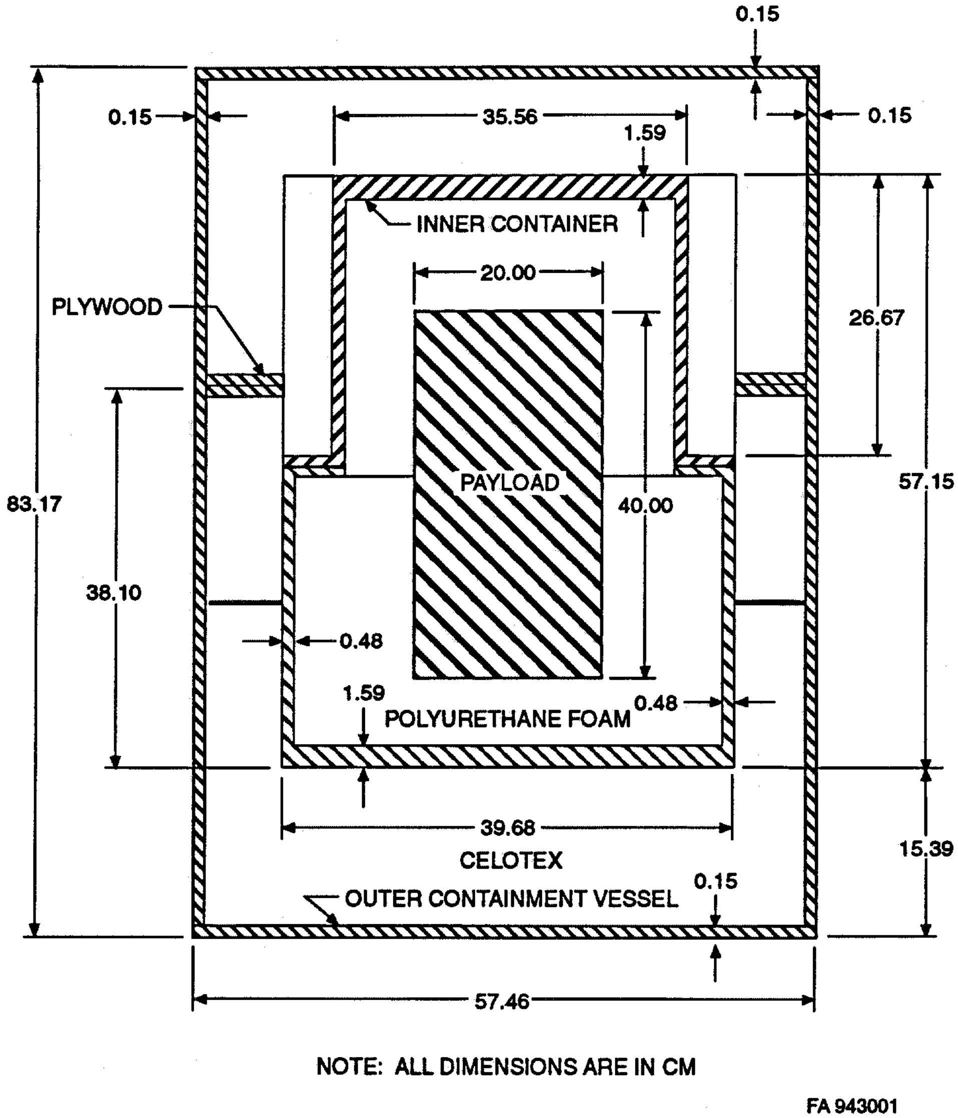

Fig. 3.1. Basic package design using cellulitic fiberboard for thermal insulation/impact limiter.

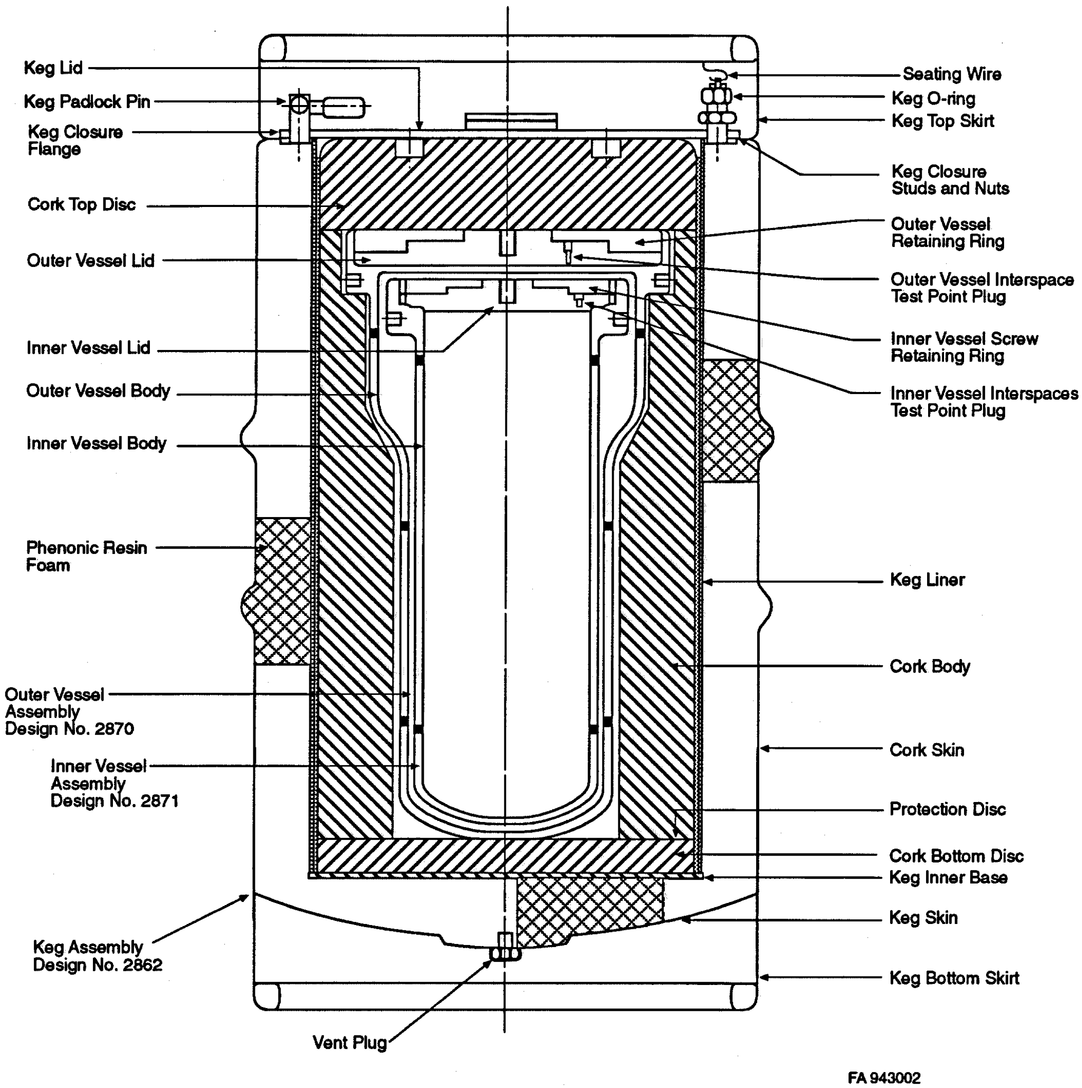

Fig. 3.2. Compartmentalized package design which reduces offgas flow to inner container during hypothetical thermal accident..

used on the outer layer. During physical thermal accident testing, some slight degradation of the inner thermal insulation does occur. But, in general, inner containers withstand this type of test with a much smaller accumulation of offgas condensate on their outer surfaces then would the simpler design described earlier.

For some packages with significant heat sources, it is very important to spread out the heat quickly such that the content does not overheat. One method that has been employed recently is to use an aluminum packing material inside the inner container to help carry off the heat coming from the source (Fig. 3.3). Aluminum is an excellent conductor of heat and thus works very well for this purpose. Initial designs for this package called for the use of aluminum shot to be used. The package is quite small, and the weight of the shot was significant when compared with the rest of the package. As an alternative, an aluminum packing very similar to aluminum straws was tried. This packing was just as effective at removing heat at only about one-third the weight of the original aluminum shot. The ability of aluminum to transfer heat so rapidly simulates a heat source the size of the inner container rather than just the size of the content. In this design, the content is not constrained within the inner container, and some shifting of the content may occur.

Another strategy used to keep heat down inside the inner container is the use of aluminum conduction bars that attach directly to the content and to the lid of the inner container (Fig. 3.4). For this container, it was necessary to hold the content in place, and a polypropylene material was selected for this duty. Placement of the content is critical such that there is good physical contact between the content and the conduction bars; therefore, the conduction bars are built into the inner container lid such that good contact there is assured. This design is effective, and there is no reason why other similar designs could not be constructed. One possibility is to build an aluminum holder into the inner container

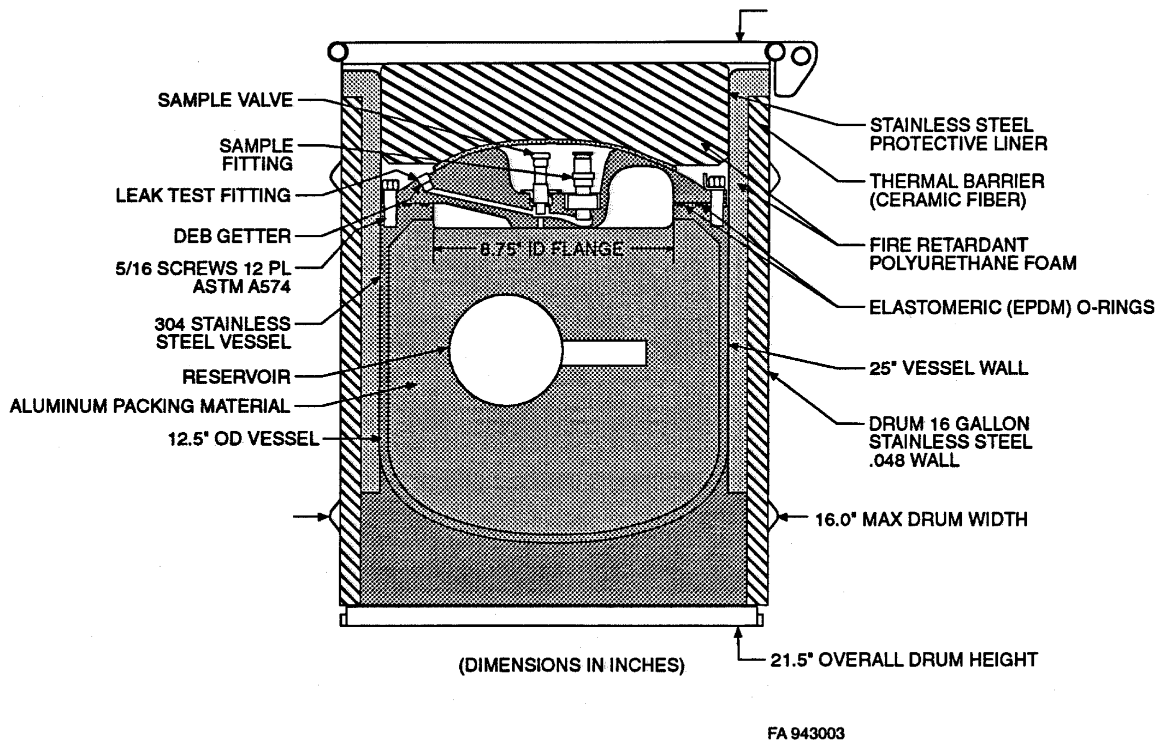

Fig 3.3. Compartmentalized package design which reduces offgas flow to inner container during hypothetical thermal accident.

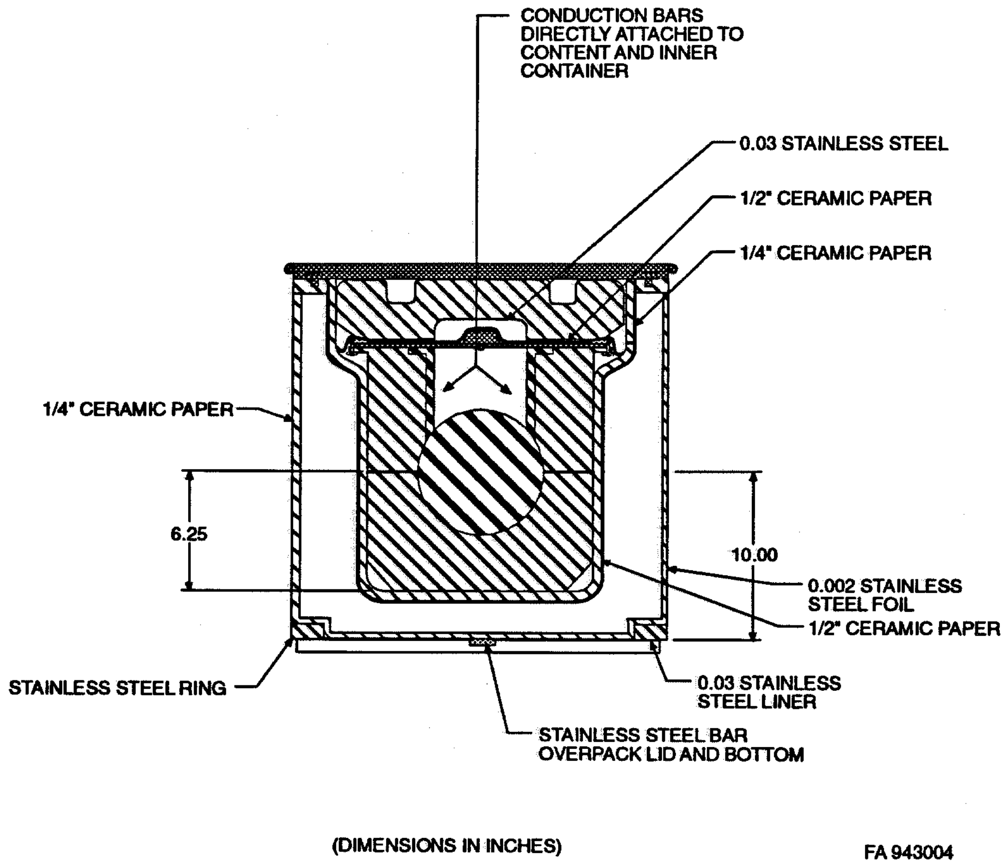

Fig. 3.4. Package design using conduction bars to direct internally generated heat out of the inner container .

with the holder attached to the inner container sidewall. Hence, both purposes of helping to remove heat while securing the content at a specific place are met.

3.3 CALCULATIONAL METHODS FOR PACKAGE DESIGN SCOPING

Several calculational methods will apply to various aspects of a proposed package design. The rigor with which it will be necessary to apply these methods will be design dependent. Internal heat sources, if large enough to be of concern, will require more calculational rigor than those without a source. The methods presented in this section are aimed toward basic design activities and are not intended for use in a SARP, although some of them may apply.

3.3.1 Rules of Thumb

A large number of packages now in the weapons complex have been certified for use. The designs of these approved packages which leads to the general rules of thumb given here. Not all materials are covered here, but general rules for a material's use may be developed by individuals who have had experience with these other materials.

Celotex^{TM}, (a fiberboard usually made of sugar cane fibers, although wood fiber is allowed), is the most commonly used thermal insulation material in radioactive materials packages in the weapons complex. Celotex^{TM} is used in many applications for several reasons. The fact that this material is very effective for both thermal insulation and impact resistance and relatively inexpensive makes it a popular choice. But, this material also has drawbacks that should be considered. Celotex^{TM} begins to decay at temperatures between 120 to 135°C (250-275 °F). When exposed to a hypothetical thermal accident, the Celotex^{TM} begins to decompose and leaves charred remains. In general, it has been found that at least

2.5 to 3.75 cm of Celotex™ will char during a typical thermal accident scenario. Offgasses from this process can find their way through the Celotex™ to the inner container, creating temperatures at the inner container significantly higher than what would be predicted by a model that considers only conduction heat transfer through the Celotex™. Experience with this material shows that a thickness of 9.0 cm (3.5 in.) is sufficient to protect the inner container from excessively high temperatures. This rule of thumb should be applied with caution because extenuating circumstances, such as open pathways for offgas travel, could cause unusually high temperatures at the package's inner container. Also, for packages weighing in excess of 200 kg, it is necessary to increase the amount of Celotex™ used. There is no proven correlation to determine how much additional insulation is needed, but increasing the Celotex™ thickness by 1 cm for every additional 20 kg of weight should be sufficient.

It is possible to estimate steady-state package surface temperatures for the noninsolated case, based on Fig. 3.5. This figure has been developed based on the discussion and subsequent example given in Subsect. 3.3.2. Steady-state surface temperatures are estimated by finding the package surface area for heat transfer (to be conservative, usually only a portion of the area available for heat transfer is used in this case, an upright cylinder with only the sides considered for heat transfer is assumed) and the package heat-generation rate. For heat-generation rates not shown, it is possible to estimate the value through interpolation. A package surface area is found on the X-axis, then a vertical line is drawn to the appropriate heat generation rate, and then a horizontal line is drawn to the Y-axis and the temperature difference is read. This temperature difference is the difference between the temperature of the surface of the package and the ambient air. It has been calculated for an ambient temperature of 37.7 °C and is most accurate when used for this condition.

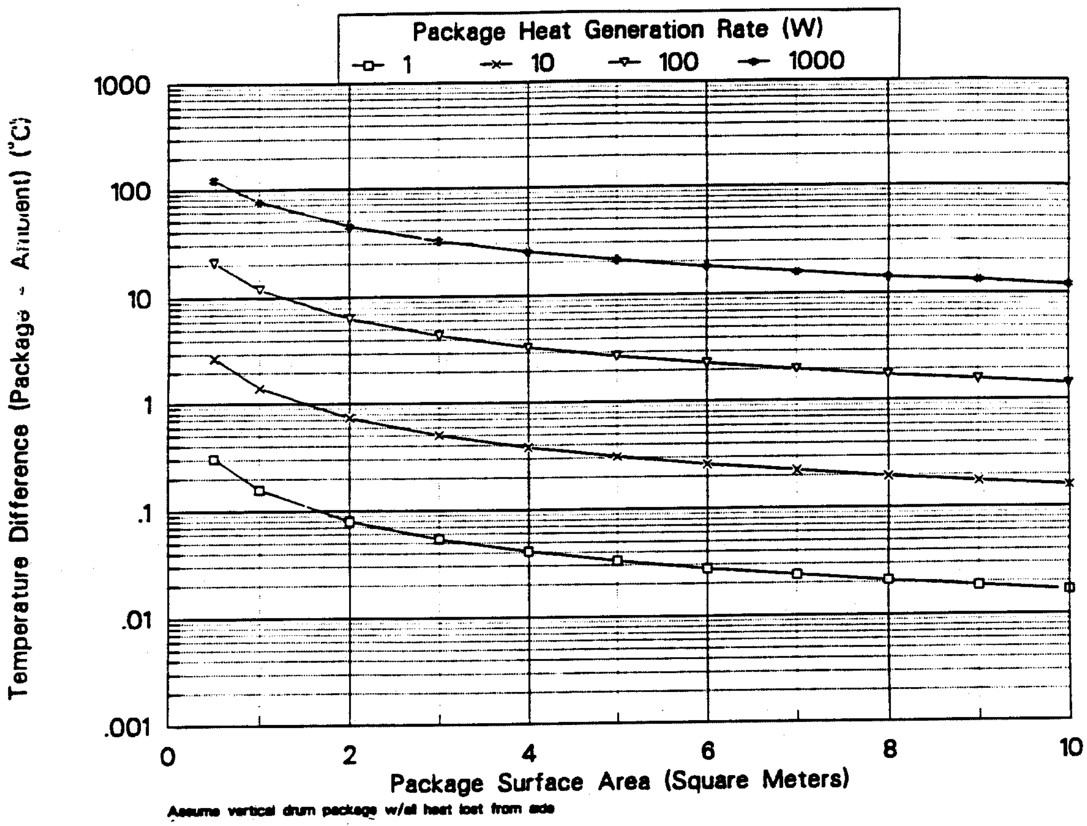

Fig. 3.5. Temperature difference (package surface - ambient) versus package surface area for several package heat-generation rates.

EXAMPLE 1 It has been proposed that a vertical cylinder package with a side surface area of 2.0 m^2 will carry a content that creates a 10.0-W heat-generation rate. Requirements call for the maximum outside temperature of the package to be no more than 50 °C when exposed to ambient conditions of 37.7 °C with no insolation. Can the package meet the criteria?

ANSWER Figure3.5, the line from 2.0 on the X-axis is followed vertically to the line that represents a heat-generation rate of 10 W. A temperature difference of between 0.7° and 0.8 °C is read from the Y-axis. This difference is a very approximate and rough estimation, but the criteria was for no more that a 22°C difference, and the difference found was less than 1°C. Thus, this package clearly will meet the criteria for this problem

3.3.2 Calculations Done by Hand

The most useful calculations for the early design stages are simple calculations done by hand or with the assistance of simple computer software such as a spreadsheet. These calculations can be performed for both normal conditions of transport and for hypothetical accident conditions.

Specific maximum temperatures on the outside of the packages for normal shaded conditions of transport are specified in 10 CFR 71.43(g) and mentioned in Subsect. 3.2.2.1. Simple procedures can be used to estimate the anticipated temperatures at the boundary of the package. Depending on how these calculations are carried out, they can be either conservative or liberal. Either type of calculation is usable as long as the designer takes into account their method (i.e. if the calculation is not conservative and the temperatures found are near the limit for the type of package being considered, a rework of the design should be considered).

To solve for the steady-state, temperature at the boundary of the package for the uninsolated, normal conditions of transport case, it is necessary to perform an energy balance on the package:

at steady-state $q_{internal} = q_{out}$

where

$q_{internal}$ = rate of internal heat generation (energy/time)

q_{out} = rate of heat transferred to surroundings (energy/time)

Presumably, the package designer knows the maximum heat that will be emitted from the package content. (NOTE: if the internal heat-generation rate is negligible, $q_{internal} = 0$, and the outer temperature of the package will be the same as the temperature of the surroundings.) This quantity of heat must now be dissipated from the package without heating the outer edge of the package past the temperatures specified in 10 CFR 71.43(g). Heat transfer to the package's surroundings will occur by both convection (natural) and radiation:

$$q_{out} = q_{conv} + q_{rad}$$

where

q_{conv} = heat lost to surroundings via convection

q_{rad} = heat lost to surroundings via radiation

Several correlations relate the convective heat transfer rate to the conditions of the convecting fluid (air). A very brief compilation of the simplest forms of these correlations is included in Table 3.1 below. The rate of heat loss due to radiation is governed by the following equation:

Table 3.1. Simple convection heat transfer coefficient for air (W/m^2-k)[4]

	Laminar[a]	Turbulent
Horizontal cylinder	$1.319\ (\Delta T/D_o)^{1/4}$	$1.243\ (\Delta T)^{1/3}$
Vertical cylinder	$1.417\ (\Delta T/L)^{1/4}$	$1.312\ (\Delta T)^{1/3}$
Flat plate, hot face up or cold face down	$1.319\ (\Delta T/L)^{1/4}$	$1.519\ (\Delta T)^{1/3}$
Flat plate, hot face down or cold face up	$0.586\ (\Delta T/L)^{1/4}$	N/A

[a] Characteristic Dimensions (L_1,D_o) are defined in Table 3.2.

Note: Use Table 3.2 for turbulent/laminar determination.

Table 3.2. Determination of convective flow regime (laminar or turbulent)

State	Laminar:	$10^3 \leq X \leq 10^9$
	Turbulent:	$10^9 \leq X \leq 10^{12}$

where

$$X = Pr \times Gr$$

and

$$Pr \equiv C_p\mu/k$$
$$Gr \equiv L^3\rho^2 g\beta\Delta T/\mu^2$$

where

L = characteristic dimension [length for horizontal plates of vertical surface, diameter for horizontal cylinders (length)]

ρ = density of fluid (mass/volume)[a]

β = coefficient of volumetric expansion [volume/(volume)(degree abs)][a]

C_p = specific heat [energy/(mass)(degree)][a]

k = thermal conductivity [energy/(time)(degree abs)][a]

μ = viscosity [mass/(length)(time)][a]

ΔT = temperature difference between surface and bulk fluid temperature (degree)

g = local acceleration of gravity ($length^2$/time)

[a] Evaluated at film temperature = $(T_{surface} + T_{bulk})/2$

Note: X, Pr, and Gr are dimensionless. Use consistent units when calculating them.

$$q_{rad} = \sigma \mathcal{F}_{12} A_1 (T_1^4 - T_2^4) ,$$

where

σ = Stefan-Boltzmann constant [energy / ((area)(time)(deg abs)^4)] ,

$\mathcal{F}_{12}$ = overall interchange factor from body 1 to body 2 ,

A_1 = area of Body 1 (area) ,

T_1 = temperature of Body 1 (deg abs) ,

T_2 = temperature of Body 2 (deg abs) .

This guide assumes that the reader is generally familiar with basic principles of heat transfer; thus, a full derivation is not given here. Suffice it to say that the preceding equation can be simplified for the current case such that the overall interchange factor is equal to the emissivity of the package, ϵ_1.

Thus, $q_{rad} = \sigma \epsilon_1 A_1 (T_1^4 - T_2^4)$.

This equation can be solved in several ways, and the method chosen will depend on the state of the package design. If no package dimensions have been set, these equations can be solved for the minimum surface area needed for the package to maintain outer shell temperatures within the limit specified by 10 CFR 71.43(g). If a package design is already on the drawing board, the surface area of the proposed design can be used to determine the maximum outer temperature. If the temperature is within allowable ranges, the design is acceptable with respect to normal condition, shadedthermal issues. If not, it will be necessary to increase the surface area of the package, resulting in a decrease in the maximum outer temperature reached by the package.

Extreme caution must be used when applying a very simplified energy balance, such as this, to a complex object, such as a radioactive shipping container. This energy balance has assumed that the surface temperature over the entire package is constant. For some simple container designs (i.e., drum-type packages), this assumption is fairly reasonable, although in no case is it conservative. For packages of complex design, design scoping techniques such as this will not be as reliable. Because this is not a conservative calculation, it will be necessary to build some conservatism into the calculation in some other way (such as considering only a portion of the exposed package surface area).

EXAMPLE 2 Calculation of steady-state, noninsolated package surface temperature based on package surface area and package internal heat generation rate.

Given: Vertical drum-type package 1.0 m tall, 0.50 m diam., internal heat-generation rate of 60 W, package external surface has an emissivity of 0.80.

Find: Approximate maximum steady-state surface temperature when ambient temperature is 37.8°C and the package is in the shade.

Assumptions: All heat lost is through the side of the package. This heat transfer area has a uniform temperature. (Note: the first of these assumptions is conservative, but the second is not).

Find heat transfer area: $A_1 = 2\pi r_1 L_1 = (2.0)(\pi)(0.25)(1.0) = 1.571\ m^2$. Assume that temperature will not rise greatly (guess 5°C), and evaluate Prandtl and Grashof numbers at 37.8 ° C (see Table 3.2).

PR = 0.72

GR = 2.100E8

X = (GR)(PR) = (0.72)(2.100E8) = 1.5128E8; therefore, Laminar

Convective heat transfer coefficient (from Table 3.1):

$$h_c = 1.417(\Delta T \ / \ L)^{1/4}$$

And, the convective heat transfer rate is then

$$q_{conv} = h_c \, A_1 \, \Delta T$$

The radiative heat transfer rate is

$$q_{rad} = \sigma \epsilon_1 A_1 (T_1^4 - T_2^4)$$

Guess a package exterior temperature of 5°C above ambient:

$$h_c = 1.417(5.0 \ / \ 1.0)^{1/4} = 2.119 \ (W/m^2\text{-}k)$$

$$q_{conv} = 2.119 \times 1.571 \times 5.0 = 16.64 \ (W)$$

$$q_{rad} = 5.670\text{x}10^{-8} \times 0.80 \times 1.571 \times (315.96^4 - 310.96^4) = 43.89 \ W$$

$$q_{total} = q_{rad} + q_{conv} = 43.89 + 16.64 = 60.53 \ W$$

Although this scenario is not exact, it is very close. The temperature at the surface of the package is estimated to be 42.8°C. As mentioned earlier, this calculation is not strictly conservative, so if the arrived at temperature was close to a limit specified by 10 CFR 71, it would be necessary to do a more realistic calculation of the temperature.

When the steady-state outer surface package temperature has been found, a simple conduction equation can be used to estimate the temperature profile inside the package. It is important to understand that this method is only an estimate, and that the equations being used were not developed for this situation. However, if this method is applied conservatively, reasonable answers can be found.

McAdams gives the simple form of the conduction equation for a cylinder with concentric widths of material wrapped around it:[4]

$$q_{cond} = (k_m \times 2 \times \pi \times L \times \Delta t) / (\mathrm{In}(x_2 / x_1))$$

where

q_{cond} = energy conducted through material (energy/time)

k_m = material thermal conductivity [(energy × length)/(time × area × degrees)I

L = length of material (length)

Δt = temperature difference (degrees)

x_1, x_2 = radial distance from cylinder center, x_2 is larger than x_1

The conduction equation used here is for the case of an infinitely long cylinder with an infinitely long heat source located at the center of the cylinder such that symmetry is preserved in the radial direction. The reason for assuming an infinitely long cylinder is that end effects are not considered. In the previous examples, we assume that all heat was lost to the surroundings only from the side of the package which in effect is ignoring end effects or assuming an infinitely long cylinder. The tricky part of applying this equation is determining the heat transfer area to be used within the package. A reasonable and conservative manner of application is to assume that heat travels only in the radial direction across insulating materials, but can travel radially and vertically across materials with relatively high thermal conductivity (inner container and outer confinement drum). This method of application is demonstrated in example 3.

<u>EXAMPLE 3</u> Under steady-state shaded conditions, estimate the temperature profile of a package containing a heat source.

Given: Vertical drum-type package 1.0 m tall, 0.50 m diam., internal heat generation of 60 W (note this is the same as package in example 2, so we already have the external surface temperature). The outer confinement drum is 0.005 m thick. Inside the confinement vessel is thermal insulation/impact limiter which is 0.095 m thick and has a thermal conductivity of 0.04 W/m-K. The inner container has an outer radius of 0.15 m, and is 0.015 m thick and is 0.75 m tall. Inside the inner container is a foam used to hold the source in place. This foam is 0.085 m thick and has a thermal conductivity of 0.26 W /m-K. The source is 0.05 m thick and 0.5 m high. All parts are cylindrically shaped. Assume that the heat generation in the source is such that the temperature throughout this source is constant. See Fig. 3.6 for a sketch of this package. The inner container and outer confinement drum are made of 304 stainless steel and have thermal conductivities of 13.4 W/m-K.

<u>ANSWER:</u> As previously mentioned, to be conservative, it should be assumed that heat travels only radially through the portions of the package which contain materials that act as insulators. This would include the thermal insulation/impact limiter material as well as the foam inside the inner container.

We will start with the outside of the package and progress in because we already know the surface temperature is approximately 42.8° C.

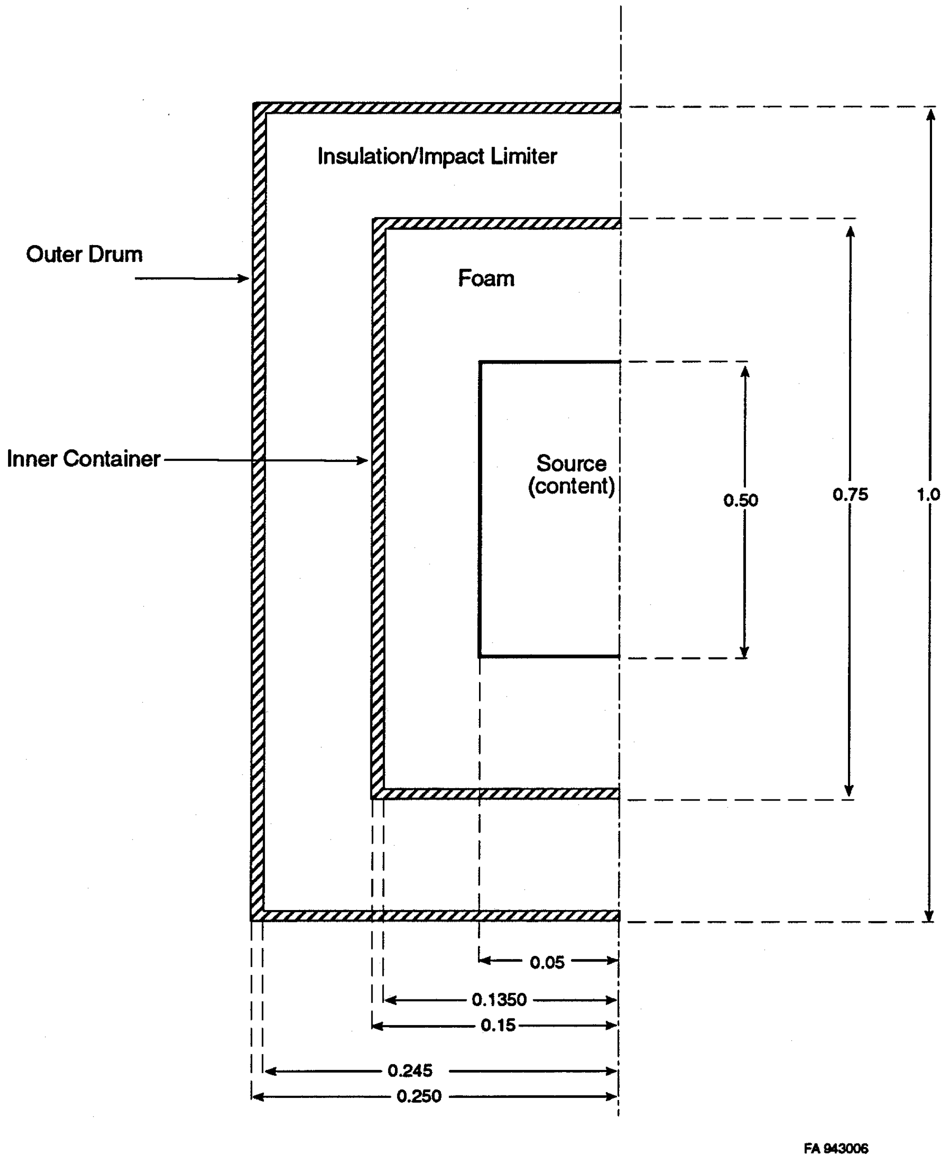

Fig. 3.6. Layout of package used for example 3.

Rearranging the conduction equation gives:

$$t_1 = \{[q_{cond} \times \ln(x_2/x_1)] / (2 \times k \times \pi \times L)]\} + t_2$$

For conduction across the outer confinement drum:

q_{cond} = 60 W

x_2 = 0.250 m

x_1 = 0.245 m

k = 13.4 W/m-K

L = 1.0 m

t_2 = 42.80° C

$$t_1 = \{[60 \text{ w} \times \ln(0.250/0.245)] / (2 \times 13.4 \text{ W/m-K} \times \pi \times 1.0)]\} + 42.8° \text{ C}$$

Note: The bracketed portion reduces to units of K, but we are adding this to number expressed in° C. This is correct because the quantity found in the bracketed portion is a change in temperature, and a change (or Δ) in temperature units K is the same as a change in° C.

t_1 = 42.81440° C or 42.81° C

It is expected that the temperature drop across a thin sheet of a highly conductive material would be small, so this answer seems reasonable. Next we need to determine the temperature drop across the thermal insulation/impact limiter. For this step the selection of L will determine how conservative our estimation is. The most conservative choice is to choose L as the height of the inner container (0.75 m).

By making this choice, we are assuming that conduction through the insulation is strictly in the radial direction from the inner container. Therefore:

$$t_1 \quad = \quad \{[q_{cond} \times \ln(x_2/x_1)] \,/\, (2 \times k \times \pi \times L)]\} + t_2$$

For conduction across the thermal insulation/impact limiter:

q_{cond} = 60 W

x_2 = 0.245 m

x_1 = 0.150 m

k = 0.04 W/m-k

L = 0.75 m

t_2 = 42.81° C

$$t_1 \quad = \quad \{[60 \text{ w} \times \ln(0.245/0.150)] \,/\, (2 \times 0.04 \text{ W/m-K} \times \pi \times 0.75)]\} + 42.81^\circ \text{ C}$$

$$t_2 \quad = \quad 199.0^\circ \text{ C}$$

Note: this is the temperature at the outer surface of the inner container

Next we determine the temperature drop across the inner container. Because the inner container is insulated on both sides by materials with relatively low thermal conductivities it is reasonable to assume that the heat will spread out evenly across this metal container. While this assumption is not strictly conservative, it is very close to being correct, and the expected temperature change across the inner container is very small. Therefore, very little error will be introduced with this estimation. We have:

$t_1 \quad = \quad \{[q_{cond} \times \ln(x_2/x_1)] / (2 \times k \times \pi \times L)]\} + t_2$

For conduction across the thermal insulation/impact limiter:

q_{cond}	=	60 W
x_2	=	0.150 m
x_1	=	0.135 m
k	=	13.4 W/m-k
L	=	0.75 m
t_2	=	199.0° C

$t_1 \quad = \quad \{[60 \text{ w} \times \ln(0.150/0.135)] / (2 \times 13.4 \text{ W/m-K} \times \pi \times 0.75)]\} + 199.0° \text{ C}$

$t_2 \quad = \quad 199.1° \text{ C}$

Note: this is the temperature at the inner surface of the inner container

Finally we determine the temperature drop across the foam inside the inner container. Because this is an insulating material it is prudent to assume heat transfer only in the radial direction from the source. Therefore, we choose L to be the length of the source, 0.50 m. This gives:

$t_1 \quad = \quad \{[q_{cond} \times \ln(x_2/x_1)] / (2 \times k \times \pi \times L)]\} + t_2$

For conduction across the thermal insulation/impact limiter:

q_{cond} = 60 W

x_2 = 0.135 m

x_1 = 0.050 m

k = 0.26 W/m-k

L = 0.50 m

t_2 = 199.1° C

t_1 = {[60 w × ln(0.135/0.050)] / (2 × 0.26 W/m-K × π × 0.50)]} + 199.1° C

t_1 = 272.1° C

Note: this is the temperature at the interface of the source and the foam surrounding it.

The temperatures found in this example are relatively high. It may be necessary to redesign the package with materials whose insulating properties are not so good. On the other hand, the calculational approach was conservative, and it is possible to find material which operate properly at these temperatures.

Each of the following examples has been extensively simplified. Techniques such as those demonstrated by these examples are very useful in the early stages of package design. However, in no way should these examples be construed as rigorous design calculations upon which certification requests can be based. Rather, these types of calculations are good for determining if the general specifications of a proposed design are worthy of further development.

3.3.3 Modeling Techniques

Complex package designs or designs for which hand calculations produce inconclusive results may require more in-depth calculational methods to ensure suitable design. More in-depth methods require that some sort of package model be developed. A wide range of techniques can be termed “models” and, in fact, exactly when a calculation ceases to be just that and becomes a model can be hard to define. For the purpose of this text, a model is defined as a set of mathematical equations used to describe a complete system that is complex enough to require a computer to solve. Models can range from several equations written on a spread sheet-type solver to advanced, three-dimensional models with literally thousands of equations used to describe the system. The following sections attempt to describe some of the techniques that can be employed to make models of packages for use during the design phase.

3.3.3.1 Simple modeling techniques

As previously mentioned, it is difficult to draw a line between simple hand calculations and so-called models. The simplest model of a package can be developed on spreadsheet software. Many software packages fit this description, but not all will suffice for the work at hand. To truly be useful, the spreadsheet package must have the capability of iterating a number of equations to find an eventual solution. If a software product does not have this capability, only “hand calculations” can be performed. This is not to say that there may be some advantages (speed and repeatability) to using the noniterating spreadsheet when iterative approaches are not required. The capability of software to iterate greatly facilitates heat transfer calculations.

One of the most common needs for an iterative scheme is to calculate heat transfer rates due to natural convection. For natural convection, fluid properties are based on a “film” temperature, which is defined as the average between the bulk fluid temperature and the temperature at the face of the solid (or liquid) from which (or to which) convection is taking place. The magnitude of the natural convection heat transfer coefficient is determined by these fluid properties. Obviously, as the heat transfer rate varies, so does the temperature at the surface of the solid (or liquid). Thus, after each iteration a new film temperature is arrived at and, with it, new fluid properties. These properties are then used to find a new heat transfer coefficient and then new heat transfer rates. The process can certainly be carried out by hand, but the use of a computer with software capable of iterating greatly enhances the speed with which the calculations are completed. This is just one example of the need for an iterative solver, but there are many other similar applications in heat transfer analysis.

Usually, during the design phase of package development, there is no need for the accuracy that these iterative methods provide. But if packages are to be certified based on analytical modeling (as opposed to physical testing), it will definitely be necessary to employ methods with this type of accuracy. It is not within the scope of this text to discuss analysis methods to be used for SARP preparation. On the other hand, it may be advantageous to the designer to make design calculations with SARP-level precision and accuracy and then also use the calculations (likely with some minor modifications) for submittal in the SARP for that package design. However, most packages, particularly complex packages, require analysis and testing by competent certifying offices.

If package surface temperatures are the only quantity that needs to be calculated, a spreadsheet-type application will usually suffice. If temperature profiles through the proposed package design are needed, it may be necessary to use a software package based on development of a model that physically represents the package. Such modeling methods include finite element, finite difference, and finite volume computer codes. For this type of analysis, a model that is representative of the package design is built using a preprocessor software package. This model may be one-, two- or three-dimensional. Material properties and boundary conditions are then defined, and the main processing (i.e., finite element solver) is completed. Results are then viewed using a postprocessor.

Each of these three solution methods has advantages and disadvantages, but for the most part they are academic. That is, any of the methods can be used for the purposes here. Before a code is chosen, it is important to make sure that the code is thoroughly verified. Verification processes differ from code to code but usually consist of a set of sample problems that have been run using the code. The problems that are used are generally chosen because they have exact solutions and can often be found in textbooks. Some codes verify by comparing solutions from one program to those of another program that has already been verified. Either method may be used, but it would also be a wise choice for the end-user to do some verification of his own because verification problems are often chosen such that each specific problem tests one specific code attribute. For example,one problem may test the convection heat transfer algorithm, whereas another may test the radiation heat transfer algorithm. But, this does not necessarily show that when both (radiation and convection) are used in a single problem they will work correctly in conjunction with each other. If a simple problem(preferably with an exact solution) that includes all of the aspects of the code that are to be used in the modeling of the package can be formulated, this method of benchmarking the code is recommended.

Codes typically selected for this type of application are termed conduction heat-transfer codes and should have the ability to handle convective and radiative boundary conditions. Some newer codes go a step beyond and actually model convection and radiation rather than just treating them as boundary conditions. These codes are certainly acceptable and may be preferable if the package design includes heat transfer design features outside of the typical layer of thermal insulation.

The complexity of the proposed package design will determine the complexity of the model needed to gather data. The majority of weapons complex packages are based on designs with a cylindrical shape. Typically, a model based on an radial coordinate system geometry (R-θ-Z) would be used. For most package designs, such as those based on the use of a simple drum, there is symmetry in the angular (θ) direction (i.e., from the drum centerline the package design appears the same in all directions). Thus, it is not necessary to model in the angular direction. That is, it is necessary only to model an infinitely thin slice of the package, and the model reduces to an R-Z model.

Depending upon the analysis that is to be performed and the quality of the data that is to be generated, it may be possible to reduce the model further to a one-dimensional model in either the R or the Z direction. To make such a simplification, one must be very careful in considering the design of the package and the information that is needed. One case in which the reduction to a one-dimensional model should not be employed is where a significant heat source is present within the package, the reason being that a one-dimensional model will not allow the heat from the source to spread through the package as it actually would. It is possible to decrease the heat load such that an appropriate quantity of heat is leaving the model, yet this method still does not properly model heat flow within the package. Although correct surface temperatures can be arrived at using this method, incorrect interior package temperatures will be calculated.

3.3.3.2 Advanced modeling techniques

At times, standard modeling techniques are not adequate to describe the situation at hand. For thermal issues, standard modeling typically describes convection, conduction, and radiation. But, there are other possibilities for heat flow. There are also cases where the heat transfer is caused by one of the three preceding methods but cannot be modeled using a standard heat transfer code. When either of these possibilities occurs, it may be necessary to apply some type of advanced heat transfer modeling technique for problem solution. Such techniques are usually applied in one of two ways. Sometimes it is possible to write a "user-supplied subroutine" to augment a pre-existing modeling package, or it may be necessary to write a stand-alone computer code to complete the needed calculations.

One common application for advanced thermal modeling techniques in the Weapons Complex Packaging Program has been for heat transfer due to offgassing of porous media during a thermal accident. Typically, the thermal conductivity of the porous media is known, but when actual physical test results are compared with analytical calculations, peak temperatures at the inner container are found to be higher in the physical test than were predicted by the analytical calculation. The media in question is known to decompose at the temperatures to which it is exposed. This decomposition process creates large quantities of offgasses. The majority of these gases escape from the package through vent holes. But some gases actually push through the porous media and through gaps between layers of the media. It is likely that most of these gases condense as they pass through the media, but apparently some of the gases do not condense until they reach the inner container. Upon condensation, heat is released and is absorbed by the inner container.

This problem has been studied for some time, and no definitive solutions have been found. However, some promising methods have been developed. One such method was an extremely conservative approach that generated an estimate of the amount of offgas produced by the process, then, using some very broad assumptions, estimated the quantity of heat that would be generated if all of these gases were condensed. All of this heat is then dumped directly on the inner container. This is such a conservative approach since the vast majority of the offgas is known to escape the package, yet, in this model, all of the gas is assumed to reach the inner container.

Another method being studied is to find, through rigorous experimentation and subsequent data analysis, an effective thermal conductivity for porous media. It is not clear if this method would take into account pathways other than directly through the porous media (i.e., gaps between layers of the media). Nonetheless, early experimental results are encouraging.

Finally, the problem has been attacked on a fundamental level, at which an attempt to actually model the flow of the gases through and around the media is made. As yet, it is not clear if this phenomenon can be successfully modeled. The mechanisms associated with it are fairly well understood, but very slight differences from one package to the next may make this form of modeling impossible. The actual gaps that exist between the layers of the media may differ significantly from one package to another. Also the exact makeup of the porous media, such as density, may also differ from one package to another. Seemingly minor differences such as these from one package to the next may make it impossible for such models to actually predict what temperatures will be seen at the inner container.

3.4 TESTING NECESSARY TO MEET 10 CFR 71 REQUIREMENTS

The material presented in this section provides general information to be considered before comprehensive testing plans are made. This section includes information on both physical and analytical methods of meeting 10 CFR 71 requirements. No attempt is made to recommend either physical or analytical methods since either can be used with positive results. Similarly, there is no recommendation about specific forms of either analytical modeling or physical testing. There is no doubt, however, that a program which includes some mix of both physical and analytical methods is most comprehensive. For such a program, the usual strategy would be to examine many orientations via analytical methods, then verify one or some of the analytical results with physical testing. Usually verification testing would be performed on the orientation which the analytical modeling suggested was the "worst case" scenario. It may not always be convenient, necessary, or possible to use both analytical and physical methods.

As was mentioned, packages must meet requirements for both normal and accidental conditions. For the most part, compliance to normal conditions is shown with analytical techniques. This is certainly not a requirement but is usually the simplest method. For accident conditions, on the other hand, compliance may be shown through physical testing, analytical modeling, or a combination. Two main reasons are given for this distinction. For normal conditions, one set of conditions is explicitly defined, and this definition includes package materials that are in a nondestructed form. On the other hand, conditions required for a hypothetical thermal accident are dependent on a series of circumstances, including a 9-m drop and a 500-kg crush test (if required, see Chap. 2). The resulting configuration must then be thermally tested. Additionally, temperatures encountered under normal conditions are such that, generally, no material decomposition takes place. Many packages experience some degradation of materials when exposed to conditions present in a hypothetical thermal accident. Because there is generally no impact on package condition due to normal thermal conditions, normal conditions of transport are not included in the section discussing physical testing. However, the testing or analysis of normal conditions of transport is still required.

3.4.1 Physical Testing Methods

In general, there are three methods of thermal physical packaging techniques that are commonly employed—pool-fire testing, radiant heat lamp testing, and furnace testing—each with its pros and cons. Without attempting to recommend one method over another, Table 3.3 gives a very brief overview of each of these methods.

Table 3.3. Advantage and disadvantages of various thermal accident test methods

Furnace testing	Advantages: Easily characterizable and controllable atmosphere.
	Disadvantages: Lag time at start-up (which can lead to package overtesting), possibly not as hot as actual fire (though as hot as regulations require).
Pool-fire burning	Advantages: Truly simulates the accident intended by regulations,
	Disadvantages: Can be affected by ambient conditions if outdoors, can cause overtesting of package.
Radiant heatlamp testing	Advantages: Easily characterizable and controllable atmosphere.
	Disadvantages: Can be hard to expose 100% of package to test conditions.

This comparison is in no way comprehensive, but an extensive review has been compiled by Koski.[8] Any of these methods can be used satisfactorily, but caution and good sense must be exercised. DOE has issued guidance[9] regarding the various forms of thermal testing and how the different types of tests will be judged in relation to 10 CFR 71.73(c).

If furnace testing is the chosen method of testing, it will be necessary to fully characterize the thermal conditions within the furnace. Some work has been documented in this area by Feldman, [10][11] and [12] which may be useful to review. If testing is to be performed by pool-fire burning, it is suggested that the reader refer to work by Keltner et al.[13][14] and [15] These reports of papers discuss many of the aspects of thermal testing that must be addressed before a successful testing program can be initiated.

Regardless of testing method, the actual testing of the package will be the culmination of a rigorous planning process. The tester must be very certain that all aspects of the requirements are met. As much pertinent data as possible should be recorded and saved to substantiate compliance.

3.4.2 Analytical Methods

Analytical modeling of packages is commonly used in SARP preparation. The types of models and modeling techniques that may be applicable for SARP documentation are very wide ranging. The following is a very brief discussion of some of the possibilities. Recognize that modeling cannot possibly take into account the total response of the package to a thermal situation, so assumptions must be made. For a SARP, these assumptions must always be conservative and the author must show that they are conservative. Many instances exist in which it is not directly clear which case is the most conservative, so it may be necessary to try several cases and then present the findings of each.

As with all subject matter included in a SARP, the use of analytical modeling techniques must be extremely well documented. This documentation includes proof that the computer code used actually operates correctly. Verification is discussed briefly in Subsect. 3.3.3.1, and for SARP use this verification is absolutely mandatory. Once verification is shown, selection of material properties must be made. It is imperative that these properties be consistent with those used elsewhere in the same SARP. Sometimes, material property given in a SARP will have a range of values, or properties used for one calculation would not be considered conservative if used in a different calculation. If one of these is the case, it may necessary to use material properties different than those found elsewhere in the SARP. If this is case, the reason(s) for using property values different than those found in other parts of the SARP must be fully justified.

Analytical techniques are often applied to demonstrate a package's response to normal conditions of transport. These typically include determining both the maximum temperature at the package boundary for the uninsolated case (only if the package contains a significant heat source) and the temperature throughout the package as a result of heating due to insolation. Results of such modeling efforts should be thoroughly presented along with input decks used in the simulation.

Applying analytical techniques to the hypothetical thermal accident is much more complicated and in many cases cannot be done without the use of extreme conservatism. This application is difficult for many reasons. Most weapons complex packages use a thermal insulation or an impact limiter, which, when exposed to high temperatures, offgasses. This offgasing, as discussed earlier, tends to change the mode of heat transfer and greatly complicates modeling efforts. Also, the hypothetical thermal accident occurs as part of a series of traumatic events that the package experiences. Before the thermal event, the package is dropped from 9-m onto an unyielding surface and in some cases is exposed to a 500-kg crush test. Most packages are deformed by one or both of these tests. It may be possible to analytically model the dropping and crushing of a package and then use the resulting mesh to model the thermal accident. But, there is still a question of how the thermal properties of the deformed materials may have changed. In some cases, there may be material property data available. Thus, if one has a thick-shelled package that resists deformation when dropped and crushed and contains thermal insulation and impact limiters that do not decompose when exposed to severe thermal situations, analytical modeling of the thermal accident is straight forward. Otherwise, the process is complicated and must be performed conservatively to prove compliance and ensure certification.

Stresses imparted to the package due to thermal conditions must be considered. Specifically, a thermal stress analysis should be performed on the normal transport model to determine if the stresses would have any effect on the packages response to accident conditions.

3.5 QUALITY ASSURANCE

Quality Assurance (QA) activities for all related packaging activities must conform with the applicable requirements of DOE Order 5700.6C, 10 CFR 71, Subpart H, or other relevant codes or standards.

The selective application of QA requirements, including thermal issues, begins during the design phase. Engineering procedures should be in place for the control of all activities during the design of the package. These approved procedures typically include control of design input, data and assumptions, document control, design verification, control of software, and interface controls.

A nonconformance and corrective action system should be in place to handle deviations or non-conformances identified during the design phase. Deviations from requirements and procedural controls should be documented and appropriate personnel identified to evaluate and disposition each deviation adequately.

A recordkeeping system should be established and records of the design must be maintained according to approved procedures.

Periodic internal assessments of the adequacy of the design control systems should be accomplished by the Engineering organization to ensure the effectiveness of these controls.

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3.6 REFERENCES

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